ICES SGCAL REPORT 2011

SCICOM STEERING GROUP ON ECOSYSTEM SURVEYS SCIENCE AND TECHNOLOGY

ICES CM 2011/SSGESST:13

REF. WGFAST, SCICOM & ACOM

Report of the Study Group on Calibration of Acoustic Instruments in Fisheries Science (SGCal)

7-8 May 2011

Reykjavik, Iceland

ICES International Council for the Exploration of the Sea

CIEM Conseil International pour l'Exploration de la Mer

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

H. C. Andersens Boulevard 44–46
DK-1553 Copenhagen V
Denmark
Telephone (+45) 33 38 67 00
Telefax (+45) 33 93 42 15
www.ices.dk
info@ices.dk

Recommended format for purposes of citation:

ICES. 2011. Report of the Study Group on Calibration of Acoustic Instruments in Fisheries Science (SGCal), 7-8 May 2011, Reykjavik, Iceland. ICES CM 2011/SSGESST:13. 18 pp.

Contents

Executive summary

The ICES Study Group on Calibration of Acoustic Instruments in Fisheries Science (SGCal) convened its second meeting in room Háteigur B of the Grand Hotel Reykjavík, Reykjavík, Iceland, on 7 and 8 May 2011. David Demer (USA) was Chair, and Tim Ryan (AUS), was Rapporteur. The Chair thanked the Rapporteur and Claire Welling (ICES) for supporting the SGCal.

Twenty-five scientists from thirteen nations participated (Annex 1). The agenda (Annex 2) spanned two days, and, according to the terms of reference (Annex 3), included presentations on calibration-related developments and was focused on reviewing draft chapters of a new Cooperative Research Report on the calibrations of acoustic instruments. The following is a summary of the CRR outline, including names of **lead** and **contributing authors**:

1) SUMMARY **(Demer)**

2) LIST OF TERMS, SYMBOLS, AND UNITS **(Demer, Jech, Macaulay, Chu)**

3) INTRODUCTION **(Jech, Bethke, Demer, Weber, Fässler, Le Bouffant)**

- 3.1) Acoustic theory (Demer, Le Bouffant)
- 3.2) Signal processing theory (Bethke, Le Bouffant)
- 3.3) Equipment
  - Echosounders (Weber, Lurton)
  - Transducer platforms (Fässler)
- 3.4) Calibration methods (Jech, LeBouffant)

4) STANDARD SPHERE CALIBRATION (Macaulay, Demer, Ryan, Scalabrin, Bethke, MacLennan)

5) CALIBRATION UNCERTAINTY (Chu, Demer)

6) CALIBRATION PROTOCOLS (Williamson, Parker-Stetter, Gauthier, Domokos, Le Bouffant, Demer, Korneliussen, Chu, Stienessen, Bernasconi, Melvin, Ryan)

7) FUTURE WORK (Chu, Melvin, Weber, Jech, Boswell, Ryan, Macaulay, Perrot, Lurton)

A list of calibration-related references was expanded (Annex 5) and copies of most were distributed to members of the group using SharePoint.

The following timeline was adopted:

31 August 2011 – Authors update draft chapters

31 October 2011 – Chair merges chapters, reduces redundancy, and adds cross-references

31 January 2012 – SG refines draft CRR

31 March 2012 – Chair edits refined draft CRR

May 2012 – SG reviews draft CRR at SGCal 2012

September 2012 – Chair submits final SGCal report and CRR to ICES

The next meeting will again be held in conjunction with WGFAST in Brest, France, from 7 May 2012.

1 Opening of the meeting

The ICES Study Group on Calibration of Acoustic Instruments in Fisheries Science (SGCal) convened its second meeting in room Háteigur B of the Grand Hotel Reykjavík, Reykjavík, Iceland, on 7 and 8 May 2011. David Demer (USA) was Chair, and Tim Ryan (AUS), was Rapporteur.

Chair opened the meeting at 08:30 on 7 April with an invitation to participants to introduce themselves and their particular calibration interests. Chair thanked Tim Ryan for agreeing to Rapporteur. Chair thanked Claire Welling (ICES) for supporting the SGCal with management of SGCal's SharePoint, and her other administrative tasks.

Chair provided an expanded list of calibration-related references (Annex 5) and called for additions. Chair solicited revisions to the agenda. The proposed agenda was adopted.

2 Terms of Reference (ToR)

The Chair called for review of the ToR. Discussions highlighted the following issues:

- The CRR must include consistent use of terms, symbols, and units. Conformance to MacLennan et al., 2002 is preferred, with some exceptions.
- The CRR should present equations in linear terms as much as possible.
- The CRR should include a section on the decibel and ramifications of logarithmic transformation.
- The CRR should be an integrated reference, not a collection of independent papers.
- The CRR will have more longevity if fundamentals and equations are presented, and software for facilitating the computations are presented in annex.
- The CRR will include 'Quick Start' sections with easy-to-follow protocols for calibrations, as well as sections with details for advanced practitioners.

The longevity of a new CRR was discussed considering the 25-year lifespan of CRR 144. Recognized is the need for a living document to augment the new CRR. Chair is to investigate with ICES the possibilities for online annex to the new CRR.

The group agreed that the new CRR should be developed around the concept of measurement uncertainty. Estimates of bias and precision, both required and realized, should guide the structure and content of the document.

3 Presentations to review recent calibration-related developments

Chair invited presentations to review recent calibration-related developments.

David MacLennan (UK) presented "Forward-scatter distortions in real-time sphere calibrations".

Pall Reynisson (Iceland) presented the results of his measurements of copper sphere target strengths.

Gavin Macaulay (Norway) demonstrated his Matlab application for calibrating EK60 and ES60 echosounders.

Dezhang Chu (USA) demonstrated his Matlab application for calculating sphere target strength (TS).

David Demer demonstrated a web application to calculate sphere *TS*.

Naig Le Bouffant (France) presented a technique for calibrating one ME70 configuration from another.

Eckhard Bethke (Germany) discussed details of calibrating an EK60.

Matteo Bernasconi (Italy) presented a new method for calibrating omnidirectional sonars.

4 Draft CRR Chapter Reviews

Chapter reviews were presents by David Demer (CRR summary; Terms, Symbols, and Units; and Theory); Mike Jech (USA; Introduction); Gavin Macaulay (Standard sphere calibration); Tim Ryan (Calibration protocols); and Dezhang Chu (Calibration Uncertainty and Future work). The group discussed each draft chapter and provided guidance to the authors for additions and refinements. The salient points from the discussion follow:

- Fundamental equations and algorithms will be detailed in the main text of the new CRR; computer programs which facilitate calibrations and data processing will be identified in annex. An online annex will be useful to connect practitioners with revised and new software as it is available.
- Because a variety of acoustic systems are calibrated in a variety of environments using a variety of apparatus, and different amounts of uncertainty may be acceptable for various equipment and applications, the new CRR will provide users with tools to minimize, estimate, and monitor uncertainty.
- The new CRR will include both analytical details and practical guides for calibrating a variety of commonly used instruments and methods.
- The CRR should be formatted as an integrated document with cross-references and minimal redundancy.
- Terms, symbols, and units should follow MacLennan et al. (2002), with some exceptions.
- Symbols should represent terms without ambiguity.
- All variables will be italicized.
- Equations should be presented in linear form, as much as practical.
- Lower- and upper-case letters will denote variables in the linear and logarithmic domains, respectively. This is a guideline, not a rule; some exceptions include state variables (e.g. T for temperature and t for time, P for pressure and p for power, and S for salinity); and Fourier transforms.
- Unique symbols are needed for depth and transducer directivity.
- The unit for salinity may be mg l-1 vs. psu.
- The accepted unit for water density is kg m-3.
- The accepted unit for frequency is Hz, cycles s-1.
- The accepted unit for power is Watt, Joule s-1.
- A rule for subscripts is needed.

- The propagation range is the distance sound travels, not necessarily the distance between objects, depending on refraction.
- Use only root-mean-square values and drop 'rms' subscript.
- The decibel will be spelled with a lower-case 'b' and will be abbreviated 'dB'.
- Log, base 10, will be abbreviated Log10.
- A 20Log_{10} definition will be added to the definition for pressure.
- Integrated volume backscattering coefficient, symbol s_a, has accepted units of $m^2\ m^{-2}$ or m^2 nautical mile^{-2}. The use of s_A will be discussed further at the next meeting of SGCal. The acronyms ABC and NASC are not needed.
- The accepted symbol and unit for pulse duration are τ and s, respectively.
- Explain effective pulse duration and correction for it.
- Define pulse length.
- Accurately define the reference for sound pressure.
- Ekhard Bethke (Germany) will provide an illustration of direction angles in Cartesian and polar coordinate systems.
- Add a diagram of an echosounder to the section describing transmit and receive gains.
- Accepted symbols for transmit and receive transducer gains are g_{ot}, g_{or}, respectively. Provide equations where $g_{ot} = g_{or} = g_0$. Standard sphere calibrations combine the effects of transmit and receive gains.
- Accepted unit for source intensity is Watt m^{-2}.
- Discuss more complex situations for surface backscattering coefficient.
- Add more references to equations.
- Add graphic for sound speed equations with error bounds.
- Add graphic for absorption equations with error bounds.
- Add sphere *TS* section in chapter on uncertainty.
- Add tables of *TS* for commonly used spheres, frequencies, sound speeds, and bandwidths.
- Group transducer platforms according to calibration techniques. Cross-reference discussions on each platform group with the appropriate protocol sections, and add practical platform-specific calibration advice.
- Change title to 'Measurements for seabed classification'; focus on calibrating measures used for classification; and reference the large body of literature.
- Anne Lebourges-Dhaussy will add section on calibrations of ADCPs.

Over the next year, draft chapters will again be available to co-authors via the SGCal SharePoint.

5 Timeline

The following timeline was adopted:

31 August 2011 – Authors update draft chapters

31 October 2011 – Chair merges chapters, reduces redundancy, and adds cross-references

31 January 2012 – SG refines draft CRR

31 March 2012 – Chair edits refined draft CRR

May 2012 – SG reviews draft CRR at SGCal 2012

September 2012 – Chair submits final SGCal report and CRR to ICES

The next meeting will again be held in conjunction with WGFAST in Brest, France, on 7 May 2012.

The second meeting of the SGCal was adjourned at 17:30 on 8 May 2011.

Annex 1: List of participants

Name		Country	E-mail
Algroy	Tonny	Norway	tonny.algroy@simrad.com
Andersen	Lars	Norway	lars.nonboe.andersen@simrad.com
Berger	Laurent	France	Laurent.Berger@ifremer.fr
Bernasconi	Matteo	Norway	matteo.bernasconi@imr.no
Bethke	Eckhard	Germany	eckhard.bethke@vti.bund.de
Chu	Dezhang	United States	Dezhang.Chu@noaa.gov
Condiotty	Jeff	United States	jeff.condiotty@simrad.com
Cutter	Randy	United States	George.Cutter@noaa.gov
Demer	David	United States	David.Demer@noaa.gov
Domokos	Réka	United States	Reka.Domokos@noaa.gov
Fässler	Sascha	The Netherlands	sascha.fassler@wur.nl
Goncharov	Sergey	Russia	sgonch@vniro.ru
Higginbottom	Ian	Australia	ian.higginbottom@echoview.com
Jarvis	Toby	Australia	tobyj@myriax.com
Jech	Mike	United States	Michael.Jech@noaa.gov
Laczkowski	Tomasz	Poland	tlaczkowski@mir.gdynia.pl
Le Bouffant	Naig	France	Naig.Le.Bouffant@ifremer.fr
Macaulay	Gavin	Norway	gavin.macaulay@imr.no
MacLennan	David	Scotland	Maclennan22@aol.com
Melvin	Gary	Canada	gary.melvin@dfo-npo.gc.ca
O'Donnell	Ciaran	Ireland	Cioran.odonnell@marine.ie
O'Driscoll	Richard	New Zealand	r.odriscoll@niwa.co.nz
Reynisson	Pall	Iceland	pall@hafro.is
Ryan	Tim	Australia	tim.ryan@csiro.au
Weber	Tom	United States	weber@ccom.unh.edu

Annex 2: Agenda – 2011 Meeting of SGCal

Saturday, 7 May

08:30-09:00	**Opening**
	Greeting, introductions, and logistics
	Refinement and adoption of agenda
09:00-10:30	Review of additional references
	Discuss emergent challenges
10:30-11:00	**Break**
11:00-12:30	Review draft chapters
	1. SUMMARY **(Demer)**
	2. LIST OF TERMS, SYMBOLS, AND UNITS **(Demer, Jech, Macaulay, Chu)**
12:30-14:00	**Lunch**
14:00-15:30	Review draft chapters
	3. INTRODUCTION **(Jech, Bethke, Demer, Weber, Fässler, Le Bouffant)**
	1. Acoustic theory **(Demer, Le Bouffant)**
	2. Signal processing theory **(Bethke, Le Bouffant)**
15:30-16:00	**Break**
16:00-17:30	3. INTRODUCTION continued **(Jech, Bethke, Demer, Weber, Fässler, Le Bouffant)**
	3. Equipment
	1. Echosounders **(Weber, Lurton)**
	2. Transducer platforms **(Fässler)**
	4. Calibration methods **(Jech, LeBouffant)**

Sunday, 8 May

08:30-10:30	Review draft chapters (cont'd)
	4. STANDARD SPHERE CALIBRATION **(Macaulay, Demer, Ryan, Scalabrin, Bethke, MacLennan)**
	David MacLennan – "Forward-scatter distortions in real-time sphere calibrations"
	Gavin Macaulay – "Matlab program for EK60 and ES60/70 calibration analysis"
	5. CALIBRATION UNCERTAINTY **(Chu, Demer)**
	David Demer – "Sphere TS: web-application and EDX investigation"
10:30-11:00	**Break**
11:00-12:30	6. CALIBRATION PROTOCOLS **(Williamson, Parker-Stetter, Gauthier, Domokos, Le Bouffant, Demer, Korneliussen, Chu, Stienessen, Bernasconi, Melvin, Ryan)**
	Eckhard Bethke – EK60 calibration program
	Naig Le Bouffant – "Calibrating one ME70 configuration from another"
	7. FUTURE WORK **(Chu, Melvin, Weber, Jech, Boswell, Ryan, Macaulay, Perrot, Lurton)**
	Matteo Bernasconi – "Omnidirectional sonar calibrations"
12:30-14:00	**Lunch**
14:00-15:30	Agree on work to be completed before the 2012 meeting of SGCal
	Identify tasks and owners
15:30-16:00	**Break**
16:00-17:30	Identify major agenda items for the 2012 meeting of SGCal; adjourn

Annex 3: SGCal terms of reference for the 2012 meeting

The Study Group on Calibration of Acoustic Instruments in Fisheries Science (SGCal) chaired by David A. Demer, USA will meet in Brest, France, from 7 May 2012 to:

a) Review the draft Cooperative Research Report (CRR) and make refinements;

b) Recommend, via the CRR, protocols to be used for acoustic-system calibrations;

c) Document, via the CRR, current theory and recommended practice of acoustic-system calibrations.

SGCal will report to WGFAST on 8 May and by 17 June 2012 (via SSGESST) for the attention of WGFAST, SCICOM and ACOM.

Supporting Information

Priority	Acoustic data are currently being collected from a variety of acoustic systems in many countries to address a range of ecosystem monitoring and stock management objectives. The ICES CRR covering this topic (CRR 144, Foote et al., 1987) is now more than 20 years old. Whereas much of the theoretical principles are still relevant, some need to be expanded to include currently used technologies (e.g. multibeam and broadbandwidth systems), and methods and standard protocols for calibrating these instruments need to be updated. There exists an urgent need to evaluate this work and to develop recommendations for protocols appropriate for calibrations of acoustic systems used in fisheries research and surveys. This need has been identified by a number of ICES Member Countries and observer countries and has been conveyed to WGFAST and SSGESST.
Scientific justification	**Term of reference a:** The ICES reference for acoustic system calibrations needs review and revision to be useful to practitioners of fisheries acoustics for stock management. The first step in this process is to review, summarize and report on the literature regarding the acoustic systems that are currently used in fisheries research and surveys. The theoretical principles for calibrating these instruments must be capitulated, and the methods currently being practiced must be evaluated. **Term of reference b:** Based the literature review, the Expert Group must make recommendations to the ICES community for standard protocols to be used for acoustic system calibrations. These protocols must cover the calibrations of all commonly used acoustic systems used in fisheries research and surveys, or be generic enough for calibrating other systems not specifically considered. The protocols must be practical and based on solid theoretical principles; and **Term of reference c):** There is a recognized need to comprehensively document the current theory and recommended practice of acoustic instrument calibrations for use in Fisheries Science, and publish them in an easily accessible report. WGFAST and SSGESST continue to recognize the difficulty of addressing these needs during full working group sessions and support the continuation of this study group comprised of experts to develop recommended methods and guidelines without delay. This Study Group will meet three times.
Resource requirements	No new resources will be required for consideration of these topics at the relevant group meetings. Having overlaps with WGFAST meetings, this SG will draw on a larger resource pool of experts which will increases efficiency in completing the objectives and reducing travel costs.

Participants	It is expected that ca. twenty five scientists from six ICES and three observer countries will initially participate in the study group. History has shown this number will likely decline to about half that number as the meeting progress, and about one fourth may be active in authoring the report. Interested industry representatives, both hardware and software suppliers) should be actively invited to participate.
Secretariat facilities	None.
Financial	No financial implications. Having overlaps with other meetings of expert groups of SSGESST increases efficiency and reduces travel costs.
Linkages to advisory committees	There are no direct linkages to the advisory committees but the work is of relevance to ACFM.
Linkages to other committees or groups	No direct linkages, however, depending on the outcome organizations such as FAO will be interested in the results.
Linkages to other organizations	WGFAST. This work should have relevance to many working, groups carrying out stock assessment of many semi-demersal and pelagic species in many ICES countries.

Annex 4: Draft Cooperative Research Report Outline

1. SUMMARY **(<u>Demer</u>)**
2. LIST OF TERMS, SYMBOLS, AND UNITS **(<u>Demer</u>, Jech, Macaulay, Chu)**
   - 2.1. Echo range
   - 2.2. Electro-acoustic efficiency
   - 2.3. Beam directivity
   - 2.4. Equivalent two-way beam angle
   - 2.5. Ambient Noise
   - 2.6. Self Noise
   - 2.7. Absorption coefficient
   - 2.8. Absorption loss
   - 2.9. Spherical spreading loss
   - 2.10. Refraction loss
   - 2.11. Attenuation
   - 2.12. Backscattering cross section
   - 2.13. Target strength
   - 2.14. Volume backscattering coefficient
   - 2.15. Volume backscattering strength
   - 2.16. Area backscattering coefficient
   - 2.17. Area backscattering strength
   - 2.18. Volume backscattering coefficient
   - 2.19. Volume backscattering strength
   - 2.20. Nautical area scattering coefficient
   - 2.21. Nautical area scattering strength
3. INTRODUCTION **(<u>Jech</u>, Bethke, Demer, Weber, Fässler, Le Bouffant, Lurton)**
   - 3.1. Acoustic theory **(<u>Demer,</u> Le Bouffant)**
     - 3.1.1. Power budget (Sonar theory, Radar theory, Combining two worlds)
       - 3.1.1.1. Transmit power
       - 3.1.1.2. Transducer efficiency
       - 3.1.1.3. Transducer directivity
       - 3.1.1.4. Echo range
       - 3.1.1.5. On-axis gain
       - 3.1.1.6. Attenuation
         - 3.1.1.6.1. Geometric spreading loss
         - 3.1.1.6.2. Absorption loss
       - 3.1.1.7. Area backscattering strength
       - 3.1.1.8. Effective receiving area
       - 3.1.1.9. Target strength (TS; dB re 1 m^2)
       - 3.1.1.10. Volume backscattering strength (S_v; dB re 1 m^{-1})
       - 3.1.1.11. Integrated volume backscattering coefficient (s_A)
       - 3.1.1.12. Biomass density (ρ; g-m^2)
       - 3.1.1.13. Surface scattering strength (S_s; dB re 1 m^2)
       - 3.1.1.14. Incidence angle (θ; º)
       - 3.1.1.15. Estimates of stochastic variables
     - 3.1.2. Signal processing theory (measurements)
       - 3.1.2.1. Echo range (r; m)
         - 3.1.2.1.1. Receiver delay
         - 3.1.2.1.2. Echo-pulse rise time
           - 3.1.2.1.2.1. Bandwidth

- 3.1.2.2. Target strength (*TS*; dB re 1 m^2)
- 3.1.2.3. Volume backscattering strength (S_v; dB re 1 m^{-1})
- 3.1.2.4. Integrated volume backscattering coefficient (s_A)
- 3.1.2.5. Biomass density (ρ; g-m^2)
- 3.1.2.6. Spatial reference
    - 3.1.2.6.1. Relative
    - 3.1.2.6.2. Geographic
- 3.1.3. Measurement-error function
    - 3.1.3.1. Accuracy (systematic error)
    - 3.1.3.2. Precision (random error)
- 3.2. Seabed classification
    - 3.2.1. Power Budget
    - 3.2.2. Measurements
        - 3.2.2.1. Surface scattering strength (S_s; dB re 1 m^2)
        - 3.2.2.2. Incidence angle (θ; º)
        - 3.2.2.3. Seabed type
        - 3.2.2.4. Spatial reference
            - 3.2.2.4.1. Relative
            - 3.2.2.4.2. Geographic
    - 3.2.3. Measurement error function
        - 3.2.3.1. Accuracy
        - 3.2.3.2. Precision
- 3.3. Echosounders **(Weber)**
    - 3.3.1. Single-beam
        - 3.3.1.1. Single-frequency
        - 3.3.1.2. Multi-frequency
        - 3.3.1.3. Broadbandwidth
    - 3.3.2. Single-beam, split-aperture
        - 3.3.2.1. Single-frequency
        - 3.3.2.2. Multi-frequency
        - 3.3.2.3. Broadbandwidth
    - 3.3.3. Multiple-beams
        - 3.3.3.1. Single-frequency
        - 3.3.3.2. Multi-frequency
        - 3.3.3.3. Broadbandwidth
    - 3.3.4. Multiple-beams, split-aperture
        - 3.3.4.1. Single-frequency
        - 3.3.4.2. Multi-frequency
        - 3.3.4.3. Broadbandwidth
- 3.4. Transducer platforms **(Fässler)**
    - 3.4.1. Vessels
        - 3.4.1.1. Hull-mount
        - 3.4.1.2. Keel-mount
        - 3.4.1.3. Pole-mount
        - 3.4.1.4. Towed-body
    - 3.4.2. Autonomous vehicles
        - 3.4.2.1. Drifters
        - 3.4.2.2. Propelled vehicles
        - 3.4.2.3. Gliders
    - 3.4.3. Stationary
        - 3.4.3.1. Buoys

3.4.3.2. Landers
3.5. Calibration methods **(Jech, Le Bouffant)**
3.5.1. Standard sphere method
3.5.2. Element vs. beamformed-data calibration
3.5.3. Hydrophone reciprocity
3.5.4. Self-reciprocity (echo from air-water interface)
3.5.5. Impedance
3.5.6. Inter-ship comparison
3.5.7. Seabed echoes
3.5.8. Self-calibrating methods
3.5.8.1. Echo-integration and in-situ target strength
3.5.8.2. Echo-counting
3.5.8.3. Multi-scattering in a cavity
3.5.9. Internal system tests and warnings (**Le Bouffant**)
3.5.9.1. Continuous impedance measurements
3.5.10. System-performance simulation (**Le Bouffant**)
3.5.11. Factory calibration
3.5.11.1. E.g., Biosonics
4. STANDARD SPHERE CALIBRATION **(Macaulay, Demer)**
4.1. Materials
4.1.1. Sphere targets
4.1.2. Apparatus
4.1.2.1. Sphere range
4.1.2.2. Centering the sphere
4.2. Method
4.2.1. Measurements
4.2.1.1. Hydrography
4.2.1.1.1. Sound speed
4.2.1.1.2. Absorption coefficient
4.2.1.2. Equivalent Beam Angle
4.2.1.2.1. Sound speed
4.2.1.2.2. Mechanical angles
4.2.1.2.3. Angle sensitivity
4.2.1.3. Impedance
4.2.1.4. Sphere *TS* vs. angular position
4.2.2. Deeply deployed transducers **(Ryan, Macaulay, Scalabrin, MacLennan)**
4.2.2.1. Towed bodies
4.2.2.2. Cast echosounders **(MacLennan)**
4.2.2.2.1. Real-time calibration
4.2.2.3. AUVs
4.2.2.4. Landers
4.3. Results
4.3.1.1. On-axis gain (*G*; dB re 1W)
4.3.1.2. Beam directivity
4.3.1.2.1. Beam widths
4.3.1.2.1.1. Off-axis angles
4.3.1.2.2. Equivalent two-way beam angle
4.3.1.3. On-axis gain correction factor (*Sa*_corr; dB re 1W)
4.3.1.3.1. Bandwidth effect
4.3.1.3.1.1. Filter delay **(Bethke)**

5. CALIBRATION UNCERTAINTY **(<u>Chu</u>, Demer)**
   - 5.1. Accuracy (systematic error)
     - 5.1.1. Sphere target strength
       - 5.1.1.1. Theoretical prediction
       - 5.1.1.2. Material
         - 5.1.1.2.1. Properties
         - 5.1.1.2.2. Homogeneity
       - 5.1.1.3. Sphericity
       - 5.1.1.4. Temperature
       - 5.1.1.5. Pressure
     - 5.1.2. Bandwidth
     - 5.1.3. Receiver delay (filter delay)
     - 5.1.4. Linearity
     - 5.1.5. Dynamic range
     - 5.1.6. Equivalent beam angle
     - 5.1.7. Time-varied gain
       - 5.1.7.1. Sound speed
       - 5.1.7.2. Absorption
       - 5.1.7.3. Geometrical spreading
       - 5.1.7.4. Refraction
       - 5.1.7.5. Bubble attenuation
     - 5.1.8. Dynamic system performance
       - 5.1.8.1. Temperature
       - 5.1.8.2. Pressure
       - 5.1.8.3. Time
       - 5.1.8.4. Transducer biofouling
   - 5.2. Precision (random error)
     - 5.2.1. System stability
     - 5.2.2. Noise
   - 5.3. Error budget function
6. CALIBRATION PROTOCOLS **(<u>Williamson</u>, Ryan, Parker-Stetter, Gauthier, Domokos, Le Bouffant, Demer, Korneliussen, Chu, Stienessen, Bernasconi, Melvin)**
   - 6.1. Simrad EK60, vessel-mounted, hull-mounted or retractable keel
     - 6.1.1. Single-beam, split-aperture
       - 6.1.1.1. Single-frequency protocol
       - 6.1.1.2. Multiple-frequency protocol
     - 6.1.2. Calibration Worksheet
       - 6.1.2.1. Metadata
   - 6.2. Simrad ES60, vessel-mounted **(<u>Ryan</u>, Williamson, Gauthier)**
     - 6.2.1. Single-beam
       - 6.2.1.1. Single-frequency protocol
       - 6.2.1.2. Multiple-frequency protocol
     - 6.2.2. Single-beam, split-aperture
       - 6.2.2.1. Single-frequency protocol
       - 6.2.2.2. Multiple-frequency protocol
     - 6.2.3. Calibration Worksheet
       - 6.2.3.1. Metadata
   - 6.3. Simrad ME70 / MS70 **(<u>Le Bouffant</u>, Demer, Korneliussen, Chu, Stienessen)**
     - 6.3.1. Multiple-beams, split-aperture, multiple-frequency, vessel-mounted
     - 6.3.2. Calibration Worksheet

Annex 5: Calibration-related References

Beamiss, G. A., Robinson, S. P., Hayman, G., and Esward, T. J. 2002. Determination of the variation in free-field hydrophone response with temperature and depth. Acta Acustica – Acustica, 88: 799–802.

Bethke, E. 2008. Calibration_and_environment. On WGFAST Calibration Topic Group sharepoint site.

Blue, J. E. 1984. Physical calibration. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 184: 19–24.

Brierley, A. S., Goss, C., Watkins, J. L., and Woodroffe, P. 1998. Variations in echosounder calibration with temperature, and some possible implications for acoustic surveys of krill biomass. CCAMLR Science, 5: 273–281.

Bodholt, H. 2002. The effect of water temperature and salinity on echo sounder measurements. ICES Symposium on Acoustics in Fisheries, Montpellier June 2002 Paper No 123.

Byard, S. 1948. Note on the Impedance Variations of an Electro-Acoustic Transducer in a Reflecting Field, Proc. Phys. Soc., vol. 61, pp. 478-480.

Carstensen, E. L. 1947. Self-reciprocity calibration of electroacoustic transducers. Journal of the Acoustical Society of America, 19: 961–965.

Carstensen, E. L., L. L. Foldy, L. L. 1947. Propagation of Sound Through a Liquid Containing Bubbles. Journal of the Acoustical Society of America, 19(3):481-501.

Chu, D., and Stanton, T. K. 1998. "Application of pulse compression techniques to broadband acoustic scattering by live individual zooplankton." Journal of the Acoustical Society of America, 104: 39–55.

Conti, S. G., Demer, D. A., Soule, M. A., and Conti, J. H. E. 2005. An improved multiple-frequency method for measuring in situ target strengths. ICES Journal of Marine Science, 62: 1636-1646.

Demer, D. A. 2004. An estimate of error for the CCAMLR 2000 survey estimate of krill biomass. Deep-Sea Research II, 51: 1237–1251.

Demer, D. A., and Hewitt, R. P. 1993. Calibration of an acoustic echo-integration system in a deep tank, with gain comparisons over standard sphere material, water temperature and time. SC-CAMLR Selected Scientific Papers, 9: 127–144.

Demer, D. A., Soule, M. A., and Hewitt, R. P. 1999. A multi-frequency method for improved accuracy and precision of *in situ* target-strength measurements. Journal of the Acoustical Society of America, 105: 2359–2376.

Demer, D. A., and Renfree, J. S. 2008. Variations in echosounder–transducer performance with water temperature. ICES Journal of Marine Science, 65: 1021–1035.

Doonan, I., Coombs, R., McClatchie, S. 2003. The absorption of sound in seawater in relation to estimation of deep-water fish biomass. ICES Journal of Marine Science, 60 (5): 1047-1055.

Dragonette, I .R., Vogt, R. H., Flax, L., and Neubauer, W. G. 1974. Acoustic reflection from elastic spheres and rigid spheres and spheroids. II. Transient analysis," Journal of the Acoustical Society of America, 55: 1130-1137.

Dragonette, L. R., Numrich, S. K., and Frank, L. J., 1981. Calibration technique for acoustic scattering measurements," Journal of the Acoustical Society of America, 69: 1186-1189.

Fernandes, P. G., and Simmonds, E. J. 1996. Practical approaches to account for receiver delay and the TVG start time in the calibration of the Simrad EK500, ICES CM 1996/B:17, 12 pp.

Foldy, L. L., Primakoff, H. 1945. A General Theory of Passive Linear Electroacoustic Transducers and the Electroacoustic Reciprocity Theorem. I. Journal of the Acoustical Society of America, 17(2): 109-120.

Foote, K. G. 1982. Optimizing copper spheres for precision calibration of hydroacoustic equipment." Journal of the Acoustical Society of America, 71: 742-747.

Foote, K. G. 1983. Maintaining precision calibrations with optimal copper spheres. Journal of the Acoustical Society of America, 73: 1054-1063.

Foote, K. G., 1989. Calibration reflector. ICES C.M. 1989/B:4.

Foote, K. G. 1990a. Spheres for calibrating an eleven-frequency acoustic measurement system." J. Const. Int. Explor. Mer, 46: 284-286.

Foote, K. G. 1990b. Bad-weather calibration of split-beam echo sounding systems. ICES C.M. 1990/B:22, 5 pp.

Foote, K. G. 1990c. Simultaneous two-sphere two-transducer calibration. ICES C.M. 1990/B:23, 6 pp.

Foote, K. G. 1991. Acoustic sampling volume. Journal of the Acoustical Society of America, 90: 959–964.

Foote, K. G. 1996. Coincidence echo statistics. Journal of the Acoustical Society of America, 99 (1): 266-271.

Foote, K. G. 2001. Calibrating a narrow band 18-kHz sonar. Woods Hole Oceanographic Institute contribution no. 10514.

Foote, K. G. 2006. Acoustic Robustness of Two Standard Spheres for Calibrating a Broadband Multibeam Sonar, Proc. Oceans 2006 MTS/IEEE, (Boston), 4pp.

Foote, K. G., and MacLennan, D. N. 1984. Comparison of copper and tungsten carbide calibration spheres. Journal of the Acoustical Society of America, 75: 612–616.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds. E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. Cooperative Research Report Const. Int. Explor. Mer, 144, 69 pp.

Foote, K. G., Naze, J., Tjotta, N., and Tjotta, S. 1987. Performance of the parametric receiving array: Effects of misalignment, 82(5): 1753-1757.

Foote, K. G., Atkins, P. R., Bongiovanni, C. C., Francis, D. T. I., Eriksen, P. K., Larsen, M., and Mortensen, T. 1999. "Measuring the frequency response function of a seven-octave bandwidth echo sounder." Proc. I.O.A., 21(1): 88–95.

Foote, K. G., Chu, D., Hammar, T. R., Baldwin, K. C., Mayer, L. A., Hufnagle, Jr., L. C., and Jech, J. M., 2005. Protocols for calibrating multibeam sonar. Journal of the Acoustical Society of America, 117 (4): 2013-2027.

Foote, K. G., Francis, D. T. I., and Atkins, P. R. 2007. Calibration sphere for low-frequency parametric sonars. Journal of the Acoustical Society of America, 121(3): 1482-1490.

Francois, R. E., and Garrison, G.R. 1982. Sound absorption based on ocean measurements, part 11: Boric acid contribution and equation for total absorption. Journal of the Acoustical Society of America, 72: 1879-1890.

Furusawa, M. 1991. Designing quantitative echosounders. Journal of the Acoustical Society of America, 90: 26–36.

Hickling, K. 1962. Analysis of echoes from a solid elastic sphere in water. Journal of the Acoustical Society of America, 34: 1582-1592.

Hobæk, H., and Nesse, T. L. 2006. Scattering from spheres and cylinders - revisited. - *In:* 29th Symposium on Physical Acoustics. Norwegian Physical Society, 16 pp.

Islas-Cital, A., Atkins, P. R., and Foo, K. Y. 2010. Standard target calibration of broad-band active sonar systems in a laboratory tank. - *In:* Oceans 2010. 10 pp.

Jech, J. M., Foote, K. G., Chu, D., and Hufnagle, L. C., Jr. 2005. Comparing two 38-kHz scientific echosounders. ICES Journal of Marine Science, 62:1168-1179.

Knudsen, H. P. 2009. Long-term evaluation of scientific-echosounder performance. ICES Journal of Marine Science, 66: 1335–1340.

Korneliussen, R. J., and Ona, E. 2002. An operational system for processing and visualizing multi-frequency acoustic data. ICES Journal of Marine Science, 59: 293–313.

Mackenzie, K. V. 1981. Nine-term equation for sound speed in the oceans. Journal of the Acoustical Society of America, 70: 807-812.

MacLean, W. R. 1940. Absolute Measurement of Sound without a Primary Standard. Journal of the Acoustical Society of America, 12:140–146.

MacLennan, D. N. 1981. The Theory of Solid Spheres as Sonar Calibration Targets. Scottish Fisheries Research, 22. 17 p.

MacLennan, D. N. 1982. Target strength measurements on metal spheres, Department of Agriculture and Fisheries for Scotland, Aberdeen (UK) Marine Lab., 11 pp.

MacLennan, D. N., Fernandes, P. G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science, 59: 365–369.

Miyanohana, Y., Ishii, K., and Furusawa, M. 1993. "Spheres to Calibrate Echo Sounders at Any Frequencies." Nippon Suisan Gakkaishi, 59: 933–942.

Mott, P. H., Roland, C. M., and Corsaro, R. D. 2002. Acoustic and dynamic mechanical properties of a polyurethane rubber. Journal of the Acoustical Society of America, 111: 1782–1790.

Nam, G. H., Cox, M. G., Harris, P. M., Robinson, S. P., Hayman, G., Beamiss, G. A., Esward, T. J., and Smith, I. M. 2007. A model for characterizing the frequency-dependent variation in sensitivity with temperature of underwater acoustic transducers from historical calibration data Meas. Sci. Technol., 18:1553–1562.

Neubauer, W. G., Vogt, R. H., and Dragonette, L. R. 1974. Acoustic reflection from elastic spheres. I. Steady-state signals." Journal of the Acoustical Society of America, 55: 1123–1129.

Nielson, R. L., Hampton, I., and Everson, I. 1980. Calibration of Hydro-acoustic Instruments, BIOMASS Handbook No. 1, SCAR/SCOR/IABO/ACMRR, 52 pp.

Ona, E., Zhao, X., Svellingen, I., and Foote, K. G., 1996. Some pitfalls of short-range standard-target calibration. ICES C.M. 1996/B:36, 19 pp.

Ona, E., Mazauric, V., and Andersen, L. N. 2009. Calibration methods for two scientific multibeam systems. ICES Journal of Marine Science, 66: 1326–1334.

Patterson, R. 1967. Using the ocean surface as a reflector for a self-reciprocity calibration of a transducer. Journal of the Acoustical Society of America, 42: 653–655.

Primakoff, H., Foldy, L. L. 1947. A General Theory of Passive Linear Electroacoustic Transducers and the Electroacoustic Reciprocity Theorem II. Journal of the Acoustical Society of America, 19(1): 50-58.

Reynisson, P. 1990. A geometric method for measuring the directivity of hull-mounted transducers. Rapp. P-v. Reun. Cons. Int. Explor. Mer., 189: 176-182.

Reynisson, P. 1998. Monitoring of equivalent beam angles of hull-mounted acoustic survey transducers in the period 1983-1995. ICES J Mar Sci., 55: 1125-1132.

Robinson, S. P., Harris, P. M., Ablitt, J., Hayman, G., Thompson, A., Lee van Buren, A., Zalesak, J. F., Drake, R. M., Isaev, A. E., Enyakov, A. M., Purcell, C., Houqing, Z., Yuebing, W., Yue, Z., Botha, P., Krüger, D. 2006. An international key comparison of free-field hydrophone calibrations in the frequency range 1 to 500 kHz. Journal of the Acoustical Society of America, 120(3): 1366-1373.

Sabin, G. A. 1956. Transducer calibration by impedance measurements. Journal of the Acoustical Society of America, 28: 705–710.

Sabin, G.A. 1964. Calibration of Piston Transducers at Marginal Test Distances. Journal of the Acoustical Society of America 36 (1): 168-173.

Sawada, K., and Furusawa, M. 1993. Precision calibration of echo sounder by integration of standard sphere echoes. J. Acoust. Soc. Japan. 14 (4): 243-249.

Simmonds, E. J. 1984. A comparison between measured and theoretical equivalent beam angles for seven similar transducers. J. Sound and Vibration. 97(1): 117–128.

Simmonds, E. J. 1990. Very accurate calibration of a vertical echo sounder: a five-year assessment of performance and accuracy. Rapp. P.-v Réun. Cons. int. Explor. Mer., 189: 183–191.

Simmonds, E. J., and MacLennan, D. N. 2005. Fisheries Acoustics: Theory and Practice, 2nd edn. Blackwell Publishing, Oxford. 437 pp.

Simrad. 1993. Simrad EK500 Scientific Echo Sounder Instruction Manual. Simrad Subsea A/S, Horten, Norway.

Simrad–Kongsberg. 2003. Simrad EK60 Scientific Echo Sounder System, Simrad Subsea A/S, Horten, Norway. 102 pp.

Simrad. 2002. Non-linear effects: recommendation for fishery research investigations, News bulletin.

Stanton, T. K., Chu, D. 2008. Calibration of broadband active acoustic systems using a single standard spherical target. Journal of the Acoustical Society of America, 124 (1): 126–138.

Sun, Z., Gimenez, G., Vray, D., and Denis, F. 1991. "Calculation of the impulse response of a rigid sphere using the physical optic method and modal method jointly." Journal of the Acoustical Society of America, 89: 10–18.

Tichy, F. E., Solli, H., and Klaveness, H. 2003. Non-linear effects in a 200-kHz sound beam and the consequences for target strength measurement. ICES J. Mar. Sci. 60: 571–574.

Urick, R. J. 1983. Principles of Underwater Sound, 3rd edn. McGraw-Hill, New York.

Vagle, S., Foote, K. G., Trevorrow, M. V., and Farmer, D. M. 1996. A Technique for Calibration of Monostatic Echosounder Systems. IEEE Journal of Oceanic Engineering, 21(3): 298-305.

Van Buren, A. L., Drake, R. M., and Paolero, A. E. 1999. Temperature dependence of the sensitivity of hydrophone standards used in international comparisons. Metrologia, 36: 281–285.

Widener, M. W. 1980. The measurement of transducer efficiency using self-reciprocity techniques. Journal of the Acoustical Society of America, 67: 1058–1060. Erratum: 68: 706.

Wilson, O. B. 1988. Introduction to Theory and Design of Sonar Transducers. Peninsula Publishing, Los Altos, CA. 191 pp.

Yasuno, Y., and Ohga, J. 2006. Temperature characteristics of electret condenser microphones, Acoust. Sci. and Tech., 27, 4.